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Abstract

Although computerized neuropsychological screening is becoming a standard for sports concussion identification and management, convergent validity studies are limited. Such studies are important for several reasons: reference to established measures is needed to establish validity; examination of the computerized battery relative to a more traditional comprehensive battery will help understand the strengths and limitations of the computer battery; and such an examination will help inform the output of the computerized battery. We compared scores on the ImPACT™ battery to a comprehensive battery of traditional neuropsychological measures and several experimental measures used in the assessment of sports-related concussion in fifty-four healthy male athletes. Convergent validity was demonstrated for four of the five ImPACT™ domain scores. Two cognitive domains often compromised as a result of mild TBI were not directly identified by the ImPACT™ battery: sustained attention and auditory working memory. Affective symptoms correlated with performance on measures of attention and working memory. In this healthy sample, the correlations between the domains covered by ImPACT™ and the neuropsychological battery supports ImPACT™ as a useful screening tool for assessing many of the cognitive factors related to mTBI. However, the data suggest other sources of data need to be considered when identifying and managing concussions.

Introduction

The use of computerized neuropsychological tests for assessment of mild traumatic brain injury (mTBI) is becoming common, particularly for student athletes. The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT™) is one of the most widely used computerized neuropsychological screening tools available. To date the reliability and validity of ImPACT™ (ImPACT™, Pittsburgh, PA) has been explored primarily by assessing the correlation between one ImPACT™ domain and one or a few conventional measures (Iverson, Franzen, Lovell, & Collins, 2003; Iverson, Lovell, & Collins, 2005; Schatz & Putz, 2006). No single study has established the construct validity of the domain scores of the ImPACT™ battery by comparing them with a full battery of traditional neuropsychological measures.

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Construct validity describes the extent to which a test may be said to measure a theoretical construct or trait such as verbal memory (Anastasi, 1997). By examining the relationships of test scores to external data, discovery of the underlying construct is possible. Establishing construct validity is considered to be a process of accruing evidence over time. Campbell and Fiske (1959) recommended that construct validity demonstrate both high correlations with tests of supposed similar constructs and low correlations with tests from which it should differ. These processes were described as ‘convergent’ and ‘discriminant’ validity, respectively. Convergent validity is thus a type of construct validity that examines the degree to which the operationalization of specific constructs (i.e., test scores) are similar to (converge on) test scores that they would be expected to be related to. For example, verbal memory tests from one battery should correlate with different tests of verbal memory in another battery when given to the same individuals at the same point in time. In contrast, discriminant validity demonstrates that different or unique traits do not correlate with each other.

Three studies have assessed aspects of concurrent validity of ImPACT™ with other traditional neuropsychological tests (Iverson, Franzen, Lovell, & Collins, 2003; Iverson, Lovell, & Collins, 2005; Schatz & Putz, 2006). Table 1 summarizes those findings, which generally support the validity of some ImPACT™ composites. The Symbol-Digit Modalities test (Smith, 1991), was shown to be strongly correlated with all composites in each of the three studies. Non-significant correlations were not reported in the original articles.

To determine the usefulness of ImPACT™ in assessing symptoms and signs of concussion, 72 high-school athletes were tested within 72 hours of receiving a sports-related concussion (Schatz, Pardini, Lovell, Collins, & Podell, 2006); concussions were diagnosed by certified athletic trainers or team physicians based on the criteria of the American Academy of Neurology. The scores of these athletes, as well as those of 66 non-concussed control athletes, were used to determine the sensitivity and sensitivity of ImPACT™. A stepwise discriminant analysis using post-concussion domain and total symptom scores found one discriminate function identifying symptom scores, Processing Speed (Visual Motor Speed), Visual Memory and Impulse Control as significant factors. Sensitivity was found to be 81.9% and specificity was 89.4%, demonstrating that this instrument can be used to differentiate concussed from non-concussed athletes.

Thus, while there is evidence that the ImPACT™ scores demonstrate adequate concurrent validity, no study has compared ImPACT™ to a comprehensive neuropsychological battery, which would allow assessment across a broader range of tests and examination of both convergent and discriminant validity. Previous studies have examined only a subgroup of tests that are known to be sensitive to brain injuries, and typically do not look at all the ImPACT™ domain scores. This study assessed the construct validity of ImPACT™ domain scores by comparing them to a more extensive battery weighted to assess the broad spectrum of cognitive sequelae commonly associated with mild TBI (mTBI) including measures of visual and verbal memory, working memory, attention, processing speed, fine motor skills and mood symptoms. A test of effort was also included. As such, the intent of this study was to provide a comprehensive test of validity that had not previously been established in a cohort of healthy athletes.

METHODS

This study was conducted as part of a larger study examining the biomechanics of concussion in college athletes. As part of the study, football and hockey athletes, as well as non-helmeted athlete controls, complete a neuropsychological battery (NP), a brief computer-based cognitive screen (ImPACT™, NP) , and functional MRI (fMRI). All participants gave written informed consent and the protocol is approved by the Dartmouth College Committee for the Protection of Human Subjects.

Participants

The study sample consisted of 54 male collegiate varsity level athletes (40 football players and 14 non-contact athletes from the golf, cross country, and crew teams). While 13 had histories of prior concussions, all were healthy at the time of baseline testing (i.e., none were recovering from a recent concussion).

Measures

As part of the research protocol, all participants completed a comprehensive neuropsychological testing and ImPACT™ testing. This was completed over one or two sessions. Testing was conducted in a soundproofed, well-ventilated office, and tests were administered by a trained examiner under the supervision of a neuropsychologist (LAF) Participants were encouraged to take breaks as needed. All data were checked by another examiner and the neuropsychologist; ImPACT™ scores were reviewed by a certified examiner (AM).

ImPACT™ battery—Version 2.0 of the web-based ImPACT™ program was administered to all athletes at the start of their regular season. We used the ImPACT™ domain scores and subtest scores, which are provided by the ImPACT™ program. Table 2 outlines the tests that comprise these domains.

Neuropsychological battery—A comprehensive battery of neuropsychological tests, which lasted approximately two hours, was administered to all participants. This battery was designed to be sensitive to cognitive functions known to show deficits or changes in the context of TBI (see Table 2 for list of tests included in the battery by domain). Domain scores were created based on the consensus opinion of three neuropsychologists from the Dartmouth Neuropsychology Laboratory. Each participant's raw test data was z-transformed using published normative data. The Z scores for each test within a given domain were averaged together to create a domain score. The battery also included self-report measures of mood (the Beck Depression Inventory, 2nd Edition (Beck-II; Beck, Steer, & Brown) and anxiety (Spielberger State-Trait Anxiety Questionnaire; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). In addition, the Word Memory Test (Green & Astner, 1995; Green, 2007; Hunt, Ferrara, Miller & Macchocchi, 2007) was administered to assess effort.

Experimental Cognitive Measures—The experimental measures consisted of measures administered as part of clinical research protocols in TBI to assess working memory and verbal episodic memory while participants were in the scanner (functional Magnetic Resonance Imaging tasks):

Working Memory (N-Back Task)—The N-back has been used in a variety of neuropsychiatric disorders including TBI (McAllister et al 1999; 2001; 2006) to assess working memory capacity. Participants view a string of consonant letters presented at a rate of one every three seconds. Four conditions are presented in this version of the task: 0-, 1-, 2-, and 3-back. The 0-back control condition has a minimal working memory load; individuals decide if the current letter matches a single target letter specified before the epoch begins. In the 1-back condition, they decide if the current letter matches the previous one. During the 2-back condition, the task is to decide whether the letter currently presented matches the letter presented two back in the sequence; in the 3-back condition, the task is to decide if the target presented matches the letter presented three back in the sequence.

Responses are signified using a button-push device. The number of correct and incorrect responses and reaction times are recorded.

Verbal Continuous Memory Task—This task is an adaptation of the paradigm used by Swick and Knight (1999) to assess memory. A list of words with a pseudo-random interstimulus interval of 5-8 seconds is viewed on a screen. Each of the words is presented twice; the second occurrence of a word may be immediately following the first (short-delay condition: 0 to 2 intervening words), or may be 9 to 18 words later in the list (long-delay condition). The subject indicates whether a word is being presented for the first time (new), or for a second time (old). Analysis is done by dividing words into 3 event types; first presentations, short delay (up to 2 words between presentations), and long delay (from 9 words to 18 words between presentations). Correct responses and reaction times are recorded.

Table 2 lists the five non-overlapping domains created for the experimental cognitive measures.

Analyses

All data were checked for accuracy, outliers, and potential covariates (e.g., team membership), and then entered into SPSS for analysis. Pearson correlations were calculated for domain scores of each battery. The subtests that made up the ImPACT™ domain (composite) scores were correlated with the traditional neuropsychological battery domain scores. No covariates were used in the analyses. As the focus was on the validity of ImPACT™, correlations within and between the other batteries are not reported. To determine linear combinations of the domain scores with the highest value, for cross-correlations, canonical correlations were calculated in SAS with domain scores from the NP battery and ImPACT™.

Results

Demographics

Ages of the participants ranged from 17-22 years, with a mean of 19.1. Forty-eight (48: 89%) reported being right handed, 4 reported being left-handed (7%) and 2 reported being ambidextrous (4%). Sport participation was primarily football (40; 74%), followed by 6 from track and field (11%), 4 golfers (7%), 3 cross-country runners (6%) and 1 rower (2%).

Forty-two athletes reported no previous concussions, while 13 reported having had at least one previously diagnosed concussion (9 had 1 concussion, 2 reported 2, and 2 reported 3) in a previous season. There were no difference between athletes with and without a prior history of concussion on any of the ImPACT™ composite scores [F (5,48) = .71, p = .62], total symptom scores [F (1,52) = .072, p = .79], or experimental measures [F (5,30) = 1.18, p = .34]. The multivariate F for the paper and pencil neuropsychological measures was significant (p = .04), with motor speed demonstrating the only significant difference [F(1,30) = 5.77, p = .02]. However, because of unequal sample sizes for some of the measures, a series of one-way ANOVA's were calculated with each test. No test was significant with the larger sample size [motor speed F(1,52) = .625, p = .43]. Results of the Word Memory Test were within normal limits for all athletes, suggesting adequate effort.

On anxiety and mood measures, both state and trait anxiety scales showed some unusual differences between groups. State and trait scores were significantly lower for the previously concussed group [state anxiety F(1,52) = 4.431, p = .040; trait anxiety F(1, 52) = 4.141, p = .047]. Means for both were within normal limits: state previously concussed mean = 24.08, *s.d.* = 5.57; state non-concussed mean = 28.81, *s.d.* = 7.44; trait concussed mean = 25.46, *s.d.* = 5.64, trait non-concussed mean = 29.88, *s.d.* = 7.14. The direction of scores is difficult to interpret and though statistically significant, the mean scores are not clinically meaningful (solidly within normal limits). For this reason we chose not to use these as covariates.

Inter-relationship of ImPACT™ Composite Scores

ImPACT™ composites (domains) were moderately but significantly correlated with each other, with reaction time and visual-motor speed demonstrating strong relationships, and the two memory composites related to each other (Table 3).

Relationship between ImPACT™ Domains and Neuropsychological Testing Domains

Table 4 shows the relationships between ImPACT and NP domains. Significant correlations were found between NP domains and all ImPACT™ domain scores except for the Impulse Control factor. Of interest, ImPACT™ Verbal Memory correlated with NP Verbal and Visual Memory, whereas the ImPACT™ Visual Memory correlated only with NP Visual Memory. The ImPACT™ Processing Speed domain score correlated with NP Processing Speed and Reaction Time. The ImPACT™ Processing Speed score also correlated with the NP Working Memory score. Both the ImPACT™ Reaction Time and Processing Speed scores demonstrated the same pattern of correlations. The NP domain scores for Motor, Attention and Impulse Control were not correlated with any ImPACT™ composite (domain) scores.

Relationship Between Individual ImPACT™ Test Scores and NP Domain Scores

To better understand how ImPACT™ related to standard NP tests, the specific ImPACT™ subtests that comprise the composite/domain scores were correlated with NP domain scores. Table 5 summarizes the relationship between ImPACT™ subtests and NP domain scores. Except for scores that make up the Impulse Control domain, at least two scores from each ImPACT™ domain were correlated with the relevant NP domain scores. NP Verbal Memory was strongly correlated with scores reflecting word-list memory, and a symbol memory task, but not the Three Letters score (of note, this score was not correlated with any of the NP domain scores). Both the Design Memory test score and the spatial memory (X-O) test score were strongly correlated with NP Visual Memory. The two scores that make up ImPACT™ Visual Motor Speed (processing speed) were related to NP Processing Speed. Note that one of the ImPACT™ scores (X-O Correct) also correlated with the NP Attention domain score. Two of the three reaction time measures correlated with the NP Reaction Time domain score. The Symbol Match Average Correct RT was not correlated with any NP domain scores. No ImPACT™ scores were correlated with the NP Motor domain. The NP Working Memory domain score was strongly correlated with ImPACT™ subtests from the Visual Memory, Processing Speed and Reaction Time composite scores, suggesting that this important function is represented across several factors within the ImPACT™ battery.

There were also several correlations between NP domains and ImPACT™ subtests that were not consistent with predictions. NP Verbal Memory showed strong relationships with the Design Memory score and the X-O correct interference score from the Processing Speed composite. NP Visual Memory correlated with the Symbol Match score (similar to Digit Symbol). In addition to predicted relationships, NP Processing Speed and Reaction Time both correlated with ImPACT™ Design Memory.

Relationship between ImPACT™, Experimental and NP Measures

ImPACT™ composites correlated with the experimental measures in a fairly predictable manner (see Table 6). All Processing Speed and Reaction Time measures were intercorrelated. The experimental Working Memory task was related to three of the five ImPACT composites, as well as NP Working Memory. There was no experimental visual memory task, and indeed, the Impact Visual Memory composite was not significantly correlated with the other experimental measures. While experimental Impulse Control was related to the ImPACT measure, it was not related to the NP measure. Of interest, although not a focus of this study, were the relationships between the experiment measures and the NP measures. The NP Verbal Memory score did not correlate with any experimental measure, while the experimental Verbal Memory score correlated with NP Attention.

Canonical Correlations

Canonical correlations were computed with domain scores from the ImPACT battery and the NP tests. As shown in Table 7, two of the five canonical dimensions were statistically significant at the .05 level, indicating a strong overall level of correlation between the ImPACT™ and NP domains. Dimension 1 had a canonical correlation of 0.80 between the sets of variables, while for Dimension 2 the canonical correlation was 0.73.

Table 8 presents the standardized canonical coefficients for the first two dimensions across both sets of variables. For the NP variables, the first canonical dimension is most strongly influenced by Visual Memory (.84), Impulse Control (−0.62), Attention (0.60) and Reaction Time (0.38), while for the second dimension Processing Speed (0.92), Verbal Memory (0.61) and Attention (0.41) contribute the most (all of the canonical correlations are presented in Table 5). For the ImPACT™ variables, the first dimension was comprised of Visual Memory (0.69), Impulse Control (0.62) and Reaction Time (0.47). For the second dimension Verbal Memory (0.79) and Processing Speed (0.50) were the most influential domains.

Dimension 2 was less consistent between variable sets, although similar patterns emerged. For the NP variables, Processing Speed was the strongest contributor, while Verbal Memory was also strong. Verbal Memory and Processing Speed were also strong contributors from the ImPACT™ set, but in reverse order.

Effect of Mood and Anxiety

Symptoms of depression and anxiety were found to be related to cognitive performance. For ImPACT™ scores, increased symptoms of current (state) anxiety were associated with poorer scores on the Processing Speed composite ($r = -.32$, $p = 0.02$), primarily due to the strong correlation with one test in the domain (Three-Letters average counted correctly; $r = -.31$, $p = .02$). The negative correlation reflects the fact that fewer numbers counted (reflecting slower speed) correlated with higher anxiety scores. On the NP measures, trait anxiety score correlated with performance in the domains of Attention ($r = -.29$, p = .035) and Impulse Control ($r = .31$, $p = .02$).

Attention domain scores from the traditional neuropsychological tests were correlated with Trait Anxiety scores. The Attention domain score was negatively correlated ($r = -.29$, $p = .03$), while Impulse Control was positively correlated ($r = .31$, $p = .02$).

At the subtest level, false positive errors from the vigilance condition of the CPT were correlated with all 3 scales (Beck-II $r = .27$, $p = .05$; State Anxiety $r = .41$, $p = <.01$; Trait Anxiety $r = .34$, $p = .01$), while false positive errors from distractibility were correlated with Trait Anxiety only ($r = .34$, $p = .01$). The PASAT B score was correlated with the Beck score ($r = -.28$, $p = .04$), while the true positive score from the Verbal Continuous Memory experimental task was correlated with scores from the Beck-II ($r = -.36$, $p = .01$) and Trait Anxiety ($r = -.29$, p = .03. Correlations were in the directions expected.

Several items from the Mood and Anxiety measures were also correlated with items from the symptom rating scale of ImPACT. For example, ImPACT's item "difficulty falling asleep" was correlated with the Beck (r = .46, p = 001), State Anxiety (r = .36, p = .009), and Trait Anxiety (r = .39, p = .004), and "feeling of nervousness" was correlated with all three scales: Beck r = .37, p = .006, State Anxiety r = .38, p = 004, Trait Anxiety r = .42, p = 001. When the symptoms were compared to the other neuropsychological and experimental test scores, convergent validity was found for three items: late sleep onset, irritability and nervousness. Sleep onset was correlated with the false positive rate on the vigilance condition of the CPT (r = .29, p = .033). Irritability was correlated with false positives on the distraction condition of the CPT (r = .28, p = .039), while nervousness was correlated with both vigilance false positives (r = .39, p = .004) and the PASAT-B score (r = .28, p = .040).

Discussion

This is the first known comparison of ImPACT™ test scores with a comprehensive neuropsychological battery and experimental cognitive measures used to assess cognitive function after TBI. Overall the results suggest good convergent and divergent validity with the ImPACT™ domains. The patterns of correlations between experimental measures and ImPACT™ scores are generally supportive of the domain structure of ImPACT™, with verbal memory and working memory showing a relationship to ImPACT™ Verbal Memory. Experimental measures of working memory also correlated with ImPACT™ Processing Speed and Impulse Control Scores. There were strong mono-trait by hetero-method correlations (similar traits by different methods) between the ImPACT™ domains and the NP domains. Inspection of the correlation matrix also demonstrated that, in general discriminant validity was also demonstrated for hetero-trait (different constructs, e.g., memory tests and the speeded tasks of Processing Speed and Reaction Time) and for both similar and different methods (mono- and hetero methods). The fact that there was a timed component for the NP Working Memory scores contributed to this domain having higher correlations with speeded tasks (Visual Motor Speed and Reaction Time), which limited the ability to discriminate between them. It was also of interest to note that experimental Verbal Memory, Reaction Time and Impulse Control demonstrated both convergent and discriminant validity, while Working Memory showed limited discriminate validity.

The pattern of correlations between ImPACT™ subtests and NP domains demonstrates the multi-factorial nature of many of the ImPACT™ subtests. The Design Memory test had significant correlations with 5 different NP domains. Further, the significant correlations between the reaction time and processing speed scores indicated that they share considerable variance. This was true for both for the NP and ImPACT™ scores (and to some degree the experimental measures), and is consistent with previous research (Iverson, Lovell & Collins, 2005). Three Letters Total Correct Letters, a subtest of Verbal Memory, did not appear to correlate with any NP subtests, although there was a trend towards significance with the motor subtests.

Of note, the NP battery identified test domains not specifically identified as factors in the ImPACT™ battery (i.e., Attention and Working Memory). These domains have been well documented as important functions related to mTBI (McAllister et al, 1999; 2001; McAllister, Flashman, McDonald, & Saykin, 2006; McDonald, Flashman & Saykin, 2002). However, there was evidence that these factors were captured within other domains measured by ImPACT™. For example, there was a significant relationship between the NP Working Memory Domain and processing speed-reaction time tasks. Thus, even without a specific working memory task(s), the processes involved in working memory appear to be represented throughout the tasks.

When looking at the absolute number of ImPACT™ subtests that correlate with each NP domain, both NP Working Memory and NP-Processing Speed domains were correlated with 5 ImPACT™ subtests each (and a sixth ImPACT™ subtest demonstrated a trend towards correlation with NP Working Memory); no other NP domain correlated with more than 4 subtests. This suggests that the ImPACT™ tests are indeed heavily loaded towards processing speed and working memory. These functions are well documented as important functions that need to be assessed in individuals with suspected mTBI.

The canonical correlation findings indicated that the data are well represented by two general dimensions. Considering both sets of variables, the first dimension includes Visual Memory and Impulse Control. When considering the NP variables, Attention is also strongly related to this dimension, while Reaction Time is the next strongest variable from the ImPACT™ dataset. Of note, these variables are related: the Attention variable is derived from accuracy scores on the CPT ("attentional accuracy"), while Reaction Time is based on speed of response on CPT-like tasks. Over all, there was relatively good agreement in the structure of the data with similar variables from each set contributing to the most significant canonical variables. The contribution of attentional accuracy to both of the NP canonical covariates is worth noting, as ImPACT™ has no such distinctly identified variable.

While overall agreement between test methods was strong, the specific coverage of function was noted to be limited within the ImPACT™ battery. Specifically, auditory working memory and sustained attention, while represented to some extent within the existing ImPACT™ domains, are not identified as specific and distinct constructs. The literature consistently identifies auditory working memory as a primary impairment in mTBI (Malojcic, Mubrin, Coric, Susnic & Spilich, 2008; McAllister, Sparling, Flashman, Guerin, Mamourian, & Saykin, 2001). Similarly, response accuracy has also been shown to be sensitive to mTBI. On the other hand, based on the current findings, reaction time is well assessed by ImPACT™. The consistent inter-relationship between processing speed and reaction time raises the question of whether there is independence of function for these two constructs.

Mood and anxiety symptoms have long been known to have an effect on neuropsychological test scores. Indeed, the pattern of findings here is consistent with previous research (Bishop, 2009; Derakshan & Eysenck, 1998). However, no previous work has shown this phenomenon to hold true for the ImPACT™ test. Furthermore, while the affective scales correlated with items from the symptom checklist in an expected pattern, none of these symptom items demonstrated similar relationships to the ImPACT™ test scores. There was convergent validity with paper-and-pencil test scores and specific symptoms, but not with experimental task results. This finding needs replication as it suggests that athletes who may be subject to anxiety (e.g., performance anxiety) may show systematic differences on baseline testing.

Finally, the relationships between paper and pencil neuropsychological tests and the experimental tests used in the fMRI scanner are unique. To our knowledge, such correlations have not been demonstrated previously. In the context of this study, these tasks helped to provide additional information pertinent to the issue of convergent validity of ImPACt™.

Several limitations of this study should be noted. First, the sample had a higher than average reading level, which may indicate a general skewing of scores upward. This was expected given this was a college sample, and so generalization to other groups should be made with caution. Within each subject, the score relationships should not be affected significantly, although variability may be lessened somewhat. The experimental tests used are not well-standardized and less is known of their psychometric properties relative to those commonly used clinically. Further, since subjects in this study were all healthy (i.e., non-concussed) athletes, the ability to generalize findings to clinical cases is limited. Future studies will explore clinical subjects as well.

Conclusions

The present study demonstrates that the cognitive domains represented by ImPACT™ have good construct validity with standard NP tests that are sensitive to cognitive functions associated with mTBI. However, the relatively narrow construct (domain) structure would seem to limit interpretation, particularly with regard to the important functions of working memory and response accuracy. Key constructs are diffusely represented which may make it difficult to interpret for the naïve consumer or untrained professional.

This study underscores the need for clinicians to limit the use of ImPACT™ to its intended purpose as a screening tool, and be cautious in interpretation of results when used in other situations. The interpretation of neuropsychological tests by non-neuropsychologists is risky. Our data shows that the nuances of the psychometrics inherent in this tool should require informed use. As a screening tool, the composite scores in ImPACT are not transparent as to function. The composite scores may hide important information contained in individual tests. Note that the recent Zurich international consensus on sports concussions recommends that for pediatric populations, neuropsychologists should be involved in administering and interpreting these types of tests (McCrory, Meeuwisse, & Johnston, et al, 2009). We would argue that the same holds true for all populations. To be clear, the use of neuropsychological tests in the assessment and management of concussions is an advance over previous grading schemes. Optimizing their use through informed supervision and training is a reasonable next step.

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Table 1

Intercorrelations between ImPACT domain scores and traditional neuropsychological tests from previous studies

	Trails A	Trails B	Symbol Digit Modalities	Digit Symbol	BVMTR
Verbal memory			$r = .46^{2**}$		Imm. Mem. $r = .50^{1*}$ Delayed Mem $r = .85^{1**}$
Visual memory			$r = .37^{2*}$		Imm. Mem. $r = .50^{1*}$ Delayed Mem $r = .85^{**}$
Processing Speed	$r = -.49^{1*}$:	$r = -.60^{1**}$:	$r = -.51^{3**}$ $r = .70^{2**}$: $r = .68^{1**}$;	$r = .54^{3**}$	
Reaction Time	$r = .64^{3**}$	$r = .44^{3*}$	$r = -.60^{2**}$:	$r = -.46^{3*}$	

* $p<.05$

** $p<.01$

(1) Iverson, G. L., Franzen, M. D., Lovell, M. R., & Collins, M. W. (2003).

(2) Iverson, G. L., Lovell, M. R., & Collins, M. W. (2005).

(3) Schatz, P. & Putz, B. O. (2006).

Table 2

Composition of domain scores for ImPACT, neuropsychological tests (NP) and experimental tests.

	ImPACT Component Scores	NP Component Scores	Experimental Component Scores
Verbal Memory	*Word Memory test* (% correct), *Symbol Match* (hidden symbols scores), *Three Letters* (total correct).	*CVLT* (trials 1-5 total; long delay total recognition discriminability).	*Verbal Continuous Memory Task* (number correct, long delay)
Visual Memory	*X's* and *0's*(total correct memory), *Design Memory* (total % correct.	*BVMT-R* (trial 1, total learning trials 1-3, delayed recall).	
Reaction Time	*X's* and *0's* (average correct RT), Symbol Match (average correct RT), *Color Match* (average correct RT).	*CPT* (Simple Reaction Time, Vigilance & Distractibility average reaction times).	*N-Back* (mean reaction times 0-back), *Verbal Continuous Memory* (mean reaction times, new condition).
Visual Motor Speed/ Processing Speed	*X's* and *0's* (total correct interference score), *Three Letters* (average counted correctly).	*DKEFS Trail Making* (sum of trials 1-3 and 5), *DKEFS Verbal Fluency* (sum of Category & Letter Fluency), *DKEFS Color Word Interference Test* (sum of 4 conditions).	*N-Back* (sum of reaction times of the 1-, 2- and 3-back).
Impulse Control	*X's* and *0's* (total incorrect – interference score), *Color Match* (number of commission errors).	*CPT* (3 conditions false positive errors), DKEFS Color Word Interference (inhibition condition errors).	*N-back* (false positives 1-back, 2-back, and 3-back).
Fine Motor Speed		*Grooved Pegboard* (right & left hand times).	
Working Memory		*PASAT* (four conditions percent correct), *DKEFS Trail Making (condition 4)*.	*N-back* (1-back, 2-back, 3-back scores, standardized & adjusted for guessing), *Verbal Continuous Memory* (working memory condition accuracy score).
Attention		*CPT* (accuracy scores of Simple Reaction Time, Vigilance and Distractibility conditions).	

BVMT-R = Brief Visual Memory Test, Revised (Benedict, 1997); CVLT = California Verbal learning test, 2nd Ed (Delis, Kramer, Kaplan, & Ober, 2000)Gordon, 1986; DKEFS = Delis Kaplan Executive Function System (Delis, Kaplan, & Kramer, 2001); Grooved Pegboard (Mitrushina, 1997); PASAT = Paced Auditory Serial Attention Test, Gronwall, 1977.

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Table 3

ImPACT™ Domain Inter-relationships ($N = 54$)

	Verbal Memory Composite	**Visual Memory Composite**	**Visual Motor Composite**	**Reaction Time Composite**	**Impulse Control Composite**
Verbal Memory Composite	1.000	**0.358**	**0.288**	0.058	−0.063
p-value		**0.008**	**0.035**	0.678	0.649
Visual Memory Composite	**0.358**	1.000	**0.282**	−0.117	0.115
p-value	**0.008**		**0.039**	0.401	0.407
Visual Motor Composite	**0.288**	**0.282**	1.000	**− 0.384**	−0.041
p-value	**0.035**	**0.039**		**0.004**	0.768
Reaction Time Composite	0.058	−0.117	**− 0.384**	1.000	**− 0.273**
	0.678	0.401	**0.004**		**0.045**
Impulse Control Composite	−0.063	0.115	−0.041	**− 0.273**	1.000
p-value	0.649	0.407	0.768	**0.045**	

Note: Significant correlations are emboldened.

Table 4

ImPACT™ and Neuropsychological (NP) Domain Intercorrelations (*p*-Values)

	ImPACT™ Domains				
	VerbalMem	**VisualMem**	**VisualMotor**	**RT**	**ImpCntl**
NPVERB_MEM	**0.40 (.00)**	0.19 (.17)	0.11 (.44)	−0.17 (.23)	−0.13 (.34)
NPWORK_MEM	0.25 (.08)	0.05 (.75)	**0.39 (.00)**	**− 0.31 (.02)**	−0.17 (.41)
NPVIS_MEM	**0.44 (.01)**	**0.59 (.00)**	0.21 (.24)	0.14 (.44)	0.20 (.27)
NP_PROCSPD	0.18 (.40)	0.18 (.19)	**0.41 (.00)**	**− 0.37 (.01)**	−0.06 (.69)
NP_ATTN	0.11 (.44)	0.14 (.32)	0.02 (.89)	−0.19 (.17)	−0.19 (.18)
NP_RT	−0.10 (.46)	0.22 (.11)	**0.34 (.01)**	**− 0.39 (.00)**	0.17 (.23)
NP_MOTOR	0.23 (.09)	0.17 (.21)	0.21 .13)	−0.15 (.27)	0.03 (.82)
NP_IMPCNT	−0.21 (.12)	−0.14 (.31)	−0.04 (.75)	0.10 (.48)	−0.02 (.89)

Notes: Correlations with *p*-values <.05 are emboldened; NPVERB_MMEM = NP verbal memory domain score; NPWORK_MEM = NP working memory domain score; NPVIS_MEM = NP visual memory domain score; NP_PROCSPD = NP processing speed domain score; NP_ATTN = NP attention domain score; NP_RT = NP reaction time domain score; NP_MOTOR = NP motor domain score; NP_IMPCNT = NP impulse control domain score

Table 5

Intercorrelations (*p*-values) between neuropsychological domain scores and ImPACT™ subtest scores, by domain

		NP VRBMEM	NP VISMEM	NP WKMEM	NP PS	NP RT	NP IMPCNT	NP ATTN	NP MOTOR
Verbal Memory Composite	Word Memory Total Percent Correct	**0.422 (0.001)**	0.274 (0.122)	0.012 (0.935)	0.085 (0.539)	−0.052 (0.711)	−0.043 (0.755)	−0.089 (0.522)	0.023 (0.866)
	Symbol Match Total Correct Hidden	**0.386 (0.004)**	**0.409 (0.018)**	0.244 (0.082)	0.073 (0.599)	−0.168 (0.224)	−0.206 (0.135)	0.184 (0.182)	0.184 (0.182)
	Three Letters Total Letters Correct	0.054 (0.701)	0.264 (0.138)	0.173 (0.219)	0.11 (0.428)	0.089 (0.521)	−0.143 (0.303)	−0.022 (0.873)	0.237 (0.084)
Visual Memory Composite	Design Memory Total Percent Correct	**0.288 (0.035)**	**0.427 (0.013)**	**0.354 (0.01)**	**0.293 (0.031)**	**0.283 (0.038)**	−0.186 (0.178)	0.243 (0.077)	0.196 (0.156)
	XO Total Correct Memory	0.081 (0.562)	**0.521 (0.002)**	−0.118 (0.403)	0.069 (0.621)	0.115 (0.406)	−0.081 (0.559)	0.046 (0.742)	0.101 (0.469)

		NP VRBMEM	NP VISMEM	NP WKMEM	NP PS	NP RT	NP IMPCNT	NP ATTN	NP MOTOR
Visual-Motor Speed Composite	XO Total Correct Interference	**0.278 (0.042)**	−0.148 (0.411)	**0.354 (0.01)**	**0.37 (0.006)**	0.163 (0.239)	−0.008 (0.953)	**0.286 (0.036)**	0.103 (0.457)
	Three Letters Average Counted Correctly	0.073 (0.599)	0.253 (0.156)	**0.352 (0.01)**	**0.373 (0.006)**	**0.332 (0.014)**	−0.044 (0.751)	−0.018 (0.815)	0.204 (0.138)
	XO Average Correct	−0.217 (0.115)	0.001 (0.995)	**−0.349 (0.011)**	**-0.449 (0.001)**	**−0.445 (0.001)**	0.042 (0.765)	−0.157 (0.258)	−0.183 (0.186)
Reaction Time Composite	Symbol Match Average Correct RT	−0.179 (0.195)	0.135 (0.454)	0.003 (0.982)	−0.011 (0.935)	-0.174 (0.208)	0.076 (0.584)	−0.117 (0.401)	0.062 (0.657)
	Color Match Average Correct RT	−0.083 (0.553)	0.14 (0.437)	**−0.392 (0.004)**	**−0.45 (0.001)**	**-0.366 (0.006)**	0.109 (0.434)	−0.193 (0.163)	−0.223 (0.104)
Impulse Control Composite	XO Total Incorrect	−0.137 (0.324)	0.184 (0.305)	−0.121 (0.394)	−0.055 (0.694)	0.167 (0.228)	-0.028 (0.839)	−0.191 (0.165)	0.036 (0.795)
	Color Match Total Commissions	−0.062 (0.654)	0.26 (0.144)	−0.045 (0.75)	−0.054 (0.700)	0.128 (0.356)	0.058 (0.679)	−0.079 (0.572)	−0.012 (0.931)

Note: Darkened boxes represent expected ImPACT subtest by NP domain relationships; emboldened scores represent significance > .05.

NP VRBMEM = NP Verbal Memory domain; NP VISMEM = NP Visual memory domain; NP WKMEM = NP Working Memory domain; NP PS = NP Processing Speed domain; NP RT = NP Reaction Time domain; NP IMPCNT = NP Impulse Control domain; NP ATTN = NP Attention domain; NP MOTOR = NP Motor domain.

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Table 6

Experimental Measures, ImPACT™ and Neuropsychological (NP) Domain Intercorrelations and *p*-Values

	Exp_PS	Exp_WM	Exp_RT	Exp_VRBM	Exp_Impulse
Memory Composite Score Verbal	0.016	**0.288**	−0.108	**0.383**	−0.046
p-value	0.907	**0.035**	0.436	**0.004**	0.739
Memory Composite Score Visual	−0.137	0.119	−0.194	0.108	−0.072
p-value	0.323	0.391	0.160	0.438	0.603
Visual Motor Composite Score	−0.143	**0.270**	**−0.271**	0.182	−0.090
p-value	0.303	**0.048**	**0.048**	0.188	0.518
Reaction Time Composite Score	**0.281**	−0.015	**0.463**	−0.212	−0.203
p-value	**0.040**	0.915	**0.000**	0.125	0.141
Impulse Control Composite Score	−0.145	**−0.493**	−0.140	0.018	**0.350**
p-value	0.296	**0.000**	0.314	0.896	**0.010**
NPVERB_MEM	−0.026	0.044	−0.156	0.095	0.131
p-value	0.852	0.753	0.259	0.494	0.346
NPVIS_MEM	−0.238	−0.048	−0.052	−0.154	−0.224
p-value	0.183	0.790	0.775	0.392	0.211
NP_WM	−0.038	**0.519**	−0.125	0.260	−0.167
p-value	0.788	**0.000**	0.378	0.063	0.236
NP_RT	**−0.386**	0.149	**−0.369**	0.143	−0.013
p-value	**0.004**	0.283	**0.006**	0.302	0.926

	Exp_PS	Exp_WM	Exp_RT	Exp_VRBM	Exp_Impulse
NP_IMPCNT	−0.188	−0.088	−0.064	−0.220	0.113
p-value	0.173	0.527	0.645	0.110	0.415
NP_ATTN	0.134	0.141	0.028	**0.269**	−0.084
p-value	0.333	0.308	0.841	**0.049**	0.545
NP_MOTOR	−0.034	0.153	−0.144	−0.018	−0.047
p-value	0.806	0.268	0.299	0.898	0.738
NP_PROCSPD	**−0.293**	0.125	**−0.317**	0.144	−0.075
p-value	**0.031**	0.368	**0.020**	0.298	0.588

Notes: Correlations with *p*-values <.05 are emboldened; NPVERB_MEM = NP verbal memory domain score; NP_WM = NP working memory domain score; NPVIS_MEM = NP visual memory domain score; NP_PROCSPD = NP processing speed domain score; NP_ATTN = NP attention domain score; NP_RT = NP reaction time domain score; NP_MOTOR = NP motor domain score; NP_Impulse = NP impulse control domain score; Exp_PS = Experimental processing speed domain score; Exp_WM = Experimental working memory domain score; Exp_RT = Experimental reaction time domain score; Exp_VRBM = Experimental verbal memory domain score; Exp_Impulse = Experimental impulse control domain score.

Table 7

Tests of Canonical Dimensions

Dimension	Canonical Corr.	Mult. F	df1	df2	p
1	**0.801789**	**1.97**	**40**	**89.972**	**0.0043**
2	**0.729172**	**1.67**	**28**	**77.139**	**0.0409**
3	0.591738	1.39	18	62.711	0.1695
4	0.543188	1.36	10	46	0.2296
5	.393117	1.10	4	24	0.3808

Table 8

Standardized Canonical Coefficients

		Dimensions	
NP		1	2
	Verbal Memory	.27	.61
	Visual Memory	.84	.20
	Processing Speed	.03	.92
	Reaction Time	.38	−.31
	Impulse Control	−.62	.05
	Attention	.60	.41
	Working Memory	−.09	.19
	Motor	.24	.05
ImPACT™			
	Verbal Memory	.14	.79
	Visual Memory	.69	.28
	Processing Speed	.39	.50
	Reaction Time	.47	.16
	Impulse Control	.62	.33